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Planar integration of free-space optical components

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In complex optical systems comprising many individual components, precise mechanical alignment becomes a difficult problem. We propose to integrate free-space optical components using planar technologies for their fabrication.

In this Communication we address the problem of how to align and package a complex optical system with many individual components. This problem occurs, for example, when free-space optics is used for an optical digital computer or switching system. To reduce problems with the alignment of many components it is necessary to reduce the number of degrees of freedom by integrating these components on common substrates. This can be achieved, for example, by using planar fabrication techniques as they are well known from the fabrication of microelectronic circuits. We start with a short comparison of electronics and optics from the viewpoint of fabrication and then present a proposal for a planar integration of free-space optical components.

The use of free-space optical interconnections in a digital computer can help to overcome some of the communications problems of today's electronic computers.[1] These are a limited temporal bandwidth, clock skew between different signals, and a limited number of input/output ports of individual chips. These problems are inherent in electronics because electronics, like waveguide optics, is essentially confined to 2-D circuits. Using a 2-D topology, it is difficult to make crossovers between wires, for example. Sophisticated layouts are required when a large number of interconnections exists in a circuit and when all of them should have the same length. The number of input/output pins of a chip is limited since I/O pads cannot be made smaller than a certain size. Consequently, with a linear arrangement of the I/O pads there is only a maximum number of ports available for one chip. However, in our comparison of optics and electronics we also have to look at the advantages of using 2-D circuits. In particular, these lie in the possibilities of using *planar* techniques such as lithography, etching, doping, and structuring for the fabrication of devices and interconnects. These techniques allow fabrication of integrated circuits, which were the basis for making electronics cheap and reliable.

Free-space optics offers the potential for building computers which do not suffer from the limitations just described for electronic systems. Using imaging optics it is possible to interconnect 2-D arrays of logic gates using the third spatial dimension. As an example, complex interconnection networks such as the perfect shuffle or the crossover network have been implemented with as many as a thousand interconnections.[2–7] No clock skew occurs since all optical signals travel the same distance with very high precision. However, the main problem of free-space optical systems lies in the fact that they are built using bulk discrete components like lenses and beam splitters. Each of these components has to be aligned individually in three spatial and three angular coordinates with very narrow tolerances.[8] This requires pushing the possibilities of mechanic alignment tools to or beyond their limits. Furthermore, it is required that a complex system remain stable with time despite varying influences, e.g., changing temperatures. This is obviously a very difficult task using today's optical and mechanical hardware. On the other hand, it raises the question of whether it is possible to use a different optical hardware which can be fabricated using similar techniques as they are used for electronic circuits.

Planar technologies have been used for several years for the fabrication of individual optical components such as lenses[9–13,26,27] and special diffraction gratings.[14–16] These components can be made of quartz glass which yields long lasting, high quality components. Using an electron-beam writer to generate the pattern of a grating yields unsurpassed resolution and precision in the submicron range. It is of interest to exploit this precision to fabricate not only individual components but rather complete subsystems or modules which integrate many components on one substrate. One module could perform, for example, one stage of an interconnection network or an array illumination operation. A complex system would consist of a number of modules rather than a lot more individual components. This would greatly reduce the number of mechanical degrees of freedom in a system. The task of aligning components on a substrate would then be left for the electron-beam writer. For the alignment of the modules with respect to each other one would have to design simple schemes which can be accomplished, for example, by an automated manufacturing system. As in a compact disk player one would have to use

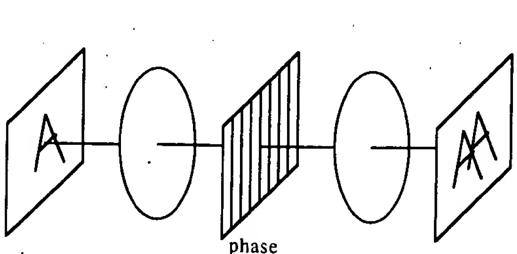

Fig. 1. Optical 4-*f* setup.

relatively simple control mechanisms to maintain the performance of a system during its operation.

Let us now consider a typical optical imaging system as an example for describing our idea of planar optics. Figure 1 shows a 4-f setup where a mask can be put in the Fourier plane for spatial filtering purposes. Our example is quite general since such a setup can be used for simple imaging but also for other applications in analog or digital data processing. For example, the same setup can be used to implement one stage of the Perfect Shuffle interconnection network in a similar way as proposed by Brenner and Huang.[5] In this case, it is assumed that the input object consists of discrete pixels on a regular grid. A binary phase grating in the Fourier plane can be used as a beam splitter. If a regular grating with a mark to space ratio of 1:1 is used and if the phase shift is exactly π for the illuminating wavelength, essentially two strong first orders are generated which yield two copies of the input image in the output plane. The period of the grating determines the shift between the two output images. It can be chosen so that in the center of the output plane one obtains the input pixels rearranged according to the interconnection scheme for the Perfect Shuffle.

For the reasons given above, we want to replace the discrete components in the setup of Fig. 1 by an integrated optical module which can be fabricated by planar technologies. To achieve this goal, the basic idea is to fold the optical signal along a zigzag path which bounces between the two mirrored surfaces of a planar substrate as indicated in Fig. 2. The substrate can be a homogeneous block of quartz glass. The optical components like lenses and beam splitters are distributed over one surface of the substrate or both. To simplify the fabrication as much as possible it would be an advantage to have alignment-critical components only on one side of the substrate and on the other side only components whose function is shift-invariant. The simplest example for such a situation would be a mirrored surface as shown in the figure.

Similar optical setups have been proposed and demonstrated by various authors for optical VLSI interconnections.[17,18] However, these cases deal with the implementation of one-to-one or one-to-many connections rather than the imaging and processing of whole images and, therefore, they lack the generality of our approach. Also, they are missing the idea of integrating free-space optical components using a monolithic substrate to integrate free-space optical components.

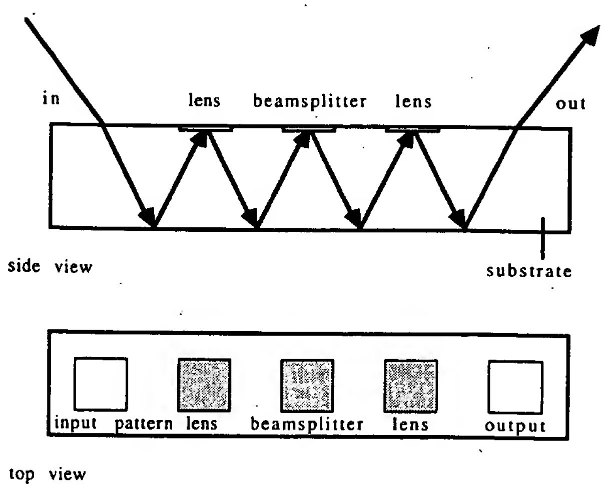

Fig. 2. Integrated optical module with free-space optical light propagation.

For the fabrication of planar lenses, beam splitters, etc., we can exploit all the physical phenomena which are used in conventional free-space optics, i.e., refraction, reflection, and diffraction. Refractive optical elements (ROEs) have been demonstrated in planar technology, for example, by Uchida *et al.*[9] and Iga *et al.*[11] In these cases the index of refraction in a glass substrate was spatially modulated by techniques such as electromigration or diffusion. ROE lenses can also be made by photochemical etching in semiconductor materials as described, for example, by Ostermayer *et al.*[12] In this case, a parabolical surface was etched in indium phosphide under the control of a laser beam. Lenses which are etched by this technique into a planar substrate may also be used in reflection by coating the substrate with a metallic layer after the etching process.

A large variety of diffractive optical elements (DOEs) have been demonstrated, mainly using conventional photographic or holographic techniques. For our purposes, other techniques are preferred which can be applied to quartz glass or semiconductor materials. These are, for example, plasma or reactive ion etching but also photochemical etching. A DOE lens can be made, e.g., using Fresnel zone patterns (FZPs). The fabrication and use of FZP based lenses have been proposed and demonstrated by various authors.[10,13,19,26,27] DOE beam splitters include, for example, regular gratings for simple split-and-shift operations but also Dammann gratings for array generation.[14,16]

The setup as shown in Fig. 2 is supposed to describe just the basic idea of using a planar integration of optical components without having the constraints of planar interconnections. Many variations are possible. For example, it is not necessary to enter the light ray under an oblique angle into the substrate. Rather, it would also be possible to enter it perpendicularly and use a prism to tilt the optical axis inside the substrate. Similarly, it would be possible to have the output beam exit under 90° to the surface of the substrate. This might be useful for putting many modules together. It is also worthwhile to point out that it is possible to put several optical circuits on one substrate. This would allow light waves to travel in different directions. Furthermore, different optical paths could be coupled together by using synthetic versions of multiplexed holograms as beam combiners. This would be basically the inverse operation to the beam splitter as described earlier. For example, it might be possible to use diffraction gratings to split an optical signal and recombine it again as in a Mach-Zehnder interferometer.

With reference to Fig. 2, it is obvious that a relationship between the diameter of the individual components, the thickness of the substrate, and the angle under which the light travels exists. As the substrate, optical flats may be used which can be fabricated practically with any thickness.

To build a complex system which consists of many modules, one has to be able to plug them together. This can be done, for example, in a way as shown in Fig. 3. A number of grooves can be etched into the substrates. An index-matching fluid might be used to ensure that the traveling light is not disturbed optically. Again, the position of the grooves

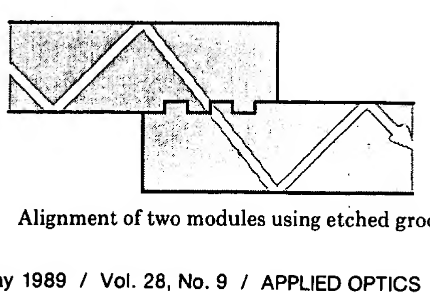

Fig. 3. Alignment of two modules using etched grooves.

can be controlled very precisely during the mask-making routine for the modules.

There are several advantages and several problems associated with our approach to integrating free-space optical components. The benefits of using an integrated module are the following:

alignment of the optical components on one substrate done by the e-beam writer with high precision;

low sensitivity of the optical path due to temperature changes;

no interfaces between different propagation media;

no or few problems with dust or humidity;

reduced number of degrees of freedom in an optical system;

alignment pads or marks can be placed on a substrate by the electron-beam writer;

possibility of placing all alignment-critical components on just one side of the substrate;

possibility of mounting several modules together.

However, there are also a number of problems associated with our approach: aberrations which might occur due to the oblique angles which are used for the signal propagation; problems with the light efficiency if DOEs are used; and problems with the fabrication of the components.

If light travels under oblique angles with respect to the optical axis aberrations result, most notably astigmatism. There may be different solutions to this problem. Using diffractive optics, for example, which involves computer generated structures, we might be able to compensate for aberration effects by the design of the DOEs. For example, it would be possible to distort the FZP patterns used for making lenses to obtain slightly elliptical patterns. Such an approach has been demonstrated by Leger *et al.*[13] They describe the use of a lenslet array made of FZPs which couples together the output of many laser diodes in a linear array. Elliptical FZPs were used to compensate for the astigmatism in the output of the individual diodes.

Another approach would be to avoid oblique angles when hitting the optical elements. This is visualized in Fig. 4 for a free-space optical setup where the light travels along a zigzag path from one component to the next. The basic idea is to use beam deflectors like prisms before and after each optical component to align the optical axis orthogonally to the components. A similar trick could be employed for planar components. Using the DOE approach the prisms can be implemented as phase gratings with a staircase profile.

The light efficiency of a module consisting of several individual components is given by the product of the efficiencies of the individual components. This may cause problems when we use DOE elements since we will always have some

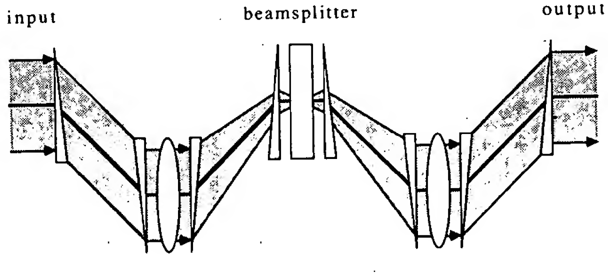

Fig. 4. Optical setup with zigzag arrangement of the optical components but orthogonal transmission of the light through the lenses and beam splitter.

losses due to the fact that light gets diffracted into higher orders. However, using components with multiple discrete phase levels, it is possible to achieve very high efficiencies for DOEs. For example, a FZP lens made of eight discrete levels can have an efficiency as high as 95%. Using sixteen levels would even yield an efficiency of 99%.

Another problem of DOEs is related to resolution of the pattern generation which is required as the first step of the fabrication process. Some patterns, most notably FZPs, require a very large space–bandwidth product. The rings of an FZP pattern have to become finer as the focal length of the FZP lens is reduced. With a limited spatial resolution of the pattern generation and lithography this implies that there is a lower limit to the f/No. of a FZP lens. As an example, we assume that we have a lithography with a minimum feature size of 5 μm. Suppose we want to make a lens with a diameter of 10 mm using eight discrete phase levels. If the illuminating wavelength is 1 μm, we can only achieve a focal length of $\sim$200 mm. This would correspond to an f/No. of 20. (Here we assumed air with a refractive index of 1 as the medium of propagation. In glass with its higher index of refraction the focal length would be reduced by a corresponding factor.) To make components with a shorter focal length we have to use a finer resolution. A feature size of 1 μm with the other parameters of our example kept constant would give a focal length of 40 mm. This would correspond to an f/No. of 4. To achieve optical systems with a larger numerical aperture it might be of interest to use refractive optical elements based on the techniques mentioned earlier.

An optical computer not only consists of optical components but also of logic devices. Therefore, we also have to consider how to integrate these devices in an overall system. Currently, most switching devices of interest for free-space optical systems are made of gallium arsenide.[20–22] Besides a discrete integration of gallium arsenide chips into a system where the interconnections are made using modules made of quartz glass other possibilities might exist. One interesting possibility is the use of silicon as the substrate material. The interesting feature of silicon is that it combines excellent mechanical and electronic properties. The latter might be useful for built-in functions on substrates like photodiodes etc., which could help with optical alignment between different modules. Recently, the possibilities of growing GaAs devices on Si have attracted a lot of attention (see, for example Ref. 23). This would also be a possibility for the integration of logic devices and interconnections in an optical computer.

The use of Si might also be attractive for integrating liquid crystal components, which could be a possibility for including the polarization of light as an additional design parameter into our model of planar optics. Polarizing beam splitters, for example, can be used for a lossless implementation of interconnections where several arrays of beams have to be handled.[24] One proposal aiming in the direction of integrating ferroelectric liquid crystal light modulators with Si-VLSI electronics was recently made by Drabik and Gaylord.[25] With Si as the substrate material we would not be able to use it in transmission in the wavelength region betwen 0.4 and 1.1 μm where Si is absorbing. In this case, one would have to use two substrates with reflective coatings between which the light travels.

Finally, we would like to summarize the ideas presented in this paper: we proposed integrating free-space optical components in a planar way to take advantage of planar fabrication techniques. Integrating optical components and possibly switching devices as well seem to be indispensable for building complex optical computing systems without the

problems of alignment and instability which are common with discrete components. Of course, any new approach to integrating optical systems will have its own problems. We mentioned several which need to be solved. However, in our opinion, none of these problems seems to be fundamental. We might not be able to achieve the high performance of a lens system which consists of several elements, for example. However, when we give the manufacturability of a complex system the highest priority, it will be necessary to sacrifice some of the performance of the individual components.

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Absolute astigmatism correction for flat field spectrographs

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Absolute astigmatism correction for flat field spectrographs is possible over an arbitrary wavelength range, while absolute defocus correction is not possible.

Although the Rowland circle mount has long been known to provide exceptional image resolution, only the two lowest-order horizontal aberrations (defocus and coma) are eliminated when a classical grating is used, their aberration terms vanishing identically at all wavelengths in this mount. No corresponding analytic mount is known for the primary vertical aberration (astigmatism); thus spectrometer designers generally accept mediocre vertical correction or employ holographic gratings whose designs usually defy algebraic analysis and require numerical optimization. When spectrometers with flat field detectors are used, the ideal focal curves are no longer circles tangent to the grating center but straight lines. The analysis below shows that this condition allows ideal astigmatism correction over an arbitrarily large wavelength range.

In Fig. 1 a typical flat field spectrometer is shown; the system lies in the x-y (principal) plane. The entrance slit A is fixed a distance r from the grating center and oriented an angle α from its normal (the Ox axis), while the diffracted wavelengths in the range $\lambda_S \leq \lambda \leq \lambda_L$ are imaged along the line $\overline{B_S B_L}$, the intersection of the planar detector and the principal plane. An ideal flat field spectrometer would be